INVESTIGATIONS IN STELLAR SPECTROSCOPY. I. A QUANTITATIVE METHOD OF CLASSIFYING STELLAR SPECTRA

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The basis of the classification of stellar spectra is at present largely empirical. In the absence of sufficient knowledge as to the modifications of spectra produced by different physical conditions it has not been possible to establish with certainty a system of classification which will represent the actual order of stellar development. Hence the stars have been classified into types simply in accordance with the characteristics of their spectra. The appearance of new lines and the disappearance of others, systematic variations in the intensities of certain lines, the presence of bands, the intensity of the continuous spectrum, and other similar criteria have been used to separate the stars into several spectral groups.

To some extent the system of classification now in general use by astronomers, that devised by the Harvard Observatory, probably has a physical basis. Thus it is well known that the differences between the spectrum of the sun and that of a star like Arcturus are very similar to those between the spectrum of the sun and that of sun-spots. In the latter case investigations have shown that a reduction of temperature is the principal agent in producing the modifications observed. Similarly the presence of bands characteristic of certain compounds which are found in the spectra of stars like α Orionis is an indication of relatively low temperature. Accordingly it seems probable that the successive types of stellar spectra, represented by the sun, Arcturus, and α Orionis, are characterized by successively lower temperatures in the gases forming the atmospheres of these stars. This does not of necessity indicate, however, that Arcturus and α Orionis have developed from stars like our sun. Lockyer and some others consider that the curve of stellar development has both an ascending and a descending branch, and that some stars of low temperature will become hotter before beginning to cool permanently. Stars which differ greatly in size and mass must almost certainly differ in the rate, and quite possibly in the order, of their development as well.

The principal lines used in the Harvard system of classification for the separation of stars into the several types are certain lines due to calcium, the more prominent lines of such metals as iron, and, most im-

portant of all, the hydrogen lines. In accordance with this system the stars are divided into seven main types designated by the letters B, A, F, G, K, M, and N, with intermediate types indicated on a scale extending from zero to ten. Thus G5 indicates a type halfway between types G and K. The B stars are characterized by helium and hydrogen absorption lines. In the A stars the helium lines disappear, the hydrogen lines reach their maximum intensity, and faint metallic lines begin to appear. These lines grow stronger and the hydrogen lines weaker in the successive types F, G, and K, the low temperature lines in particular increasing rapidly in intensity between the G and K types. The sun is a typical G0 star. The M and N stars are distinguished by the presence of bands, in the one case of a compound of titanium, and in the other of carbon.

The Harvard system of classification in general meets the requirements of spectral observations in a most excellent way. There is, however, in published descriptions of its application a serious lack of numerical relationships between the intensities of the lines compared, and as a result a considerable uncertainty arises in the determination of spectral types. Since in many astronomical investigations a comparison is instituted between stars of very closely the same type it is important to reduce the classification of stellar spectra to as accurate a basis as possible. The following brief description of the method employed at Mount Wilson is given for two purposes: first, because it replaces to a considerable extent direct estimations of spectral type by numerical estimates of relative line intensity which may be made with much higher accuracy; and second, because the method provides the material upon which several investigations have been based. It was devised in large measure by Dr. Kohlschütter, and has been used with but slight modifications since his departure from Mount Wilson.

The material available for classification purposes consists of several thousand photographs of stellar spectra taken with a one prism slit spectrograph and the sixty-inch reflector. About two-thirds of these spectra are of types succeeding F0. On most of the photographs the region of spectrum in best definition extends from λ 4200 to λ 4900. It includes, therefore the two hydrogen lines $H\gamma$ and $H\beta$, the important calcium line at λ 4227, and some of the most prominent iron lines in the entire spectrum. Since the hydrogen lines show a rapid decrease in intensity with the successive types F, G, K and M, and form by far the most important criterion in the derivation of spectral type, accurate determinations of their intensity relative to other lines in the spectrum are essential. Accordingly several adjacent iron lines have been selected

which show but a moderate change of intensity in these types, and estimates are made on an arbitrary scale, extending from zero to ten, of the differences in intensity between the hydrogen lines and this selected list. The calcium line λ 4227 is also compared with $H\gamma$ in the types F0 to G5, beyond G5 the differences becoming too great to provide satisfactory determinations. The list of pairs of lines finally adopted for classification purposes is given in Table I.

TABLE I

Lines Compared	*Range of Type*
$H\gamma$ and λ 4227, *Ca*	F0 to G5
$H\gamma$ " λ 4326, *Fe*	F3 to Ma
$H\gamma$ " λ 4352, *Fe, Mg*	F0 to Ma
$H\gamma$ " λ 4383, *Fe*	F0 to G5
$H\gamma$ " λ 4405, *Fe*	F3 to Ma
$H\beta$ " λ 4872, *Fe*	G0 to Ma
$H\beta$ " λ 4957, *Fe*	G0 to Ma

The scale of classification was adapted to the Harvard system by selecting a considerable number of stars for which Harvard determinations were available, and making estimates of the relative intensities of these pairs of lines in the stars selected. The values were then plotted against the average types of these stars, and smooth curves were drawn through the several points. These curves provide the means of converting determinations of relative line intensity into determinations of spectral type. The curves are shown in figure 1. For reasons which will appear later, they are based upon stars of large proper motion alone, and the material may, therefore, be regarded as homogeneous in character.

To illustrate the use of these curves I have selected as examples the stars Groom. 3357, Piazzi 0^h130, Groom. 145 and Lal. 19022. The estimated differences of intensity for these stars, as determined from three photographs of their spectra, are given in Table II.

TABLE II

	$\frac{4226}{H\gamma}$	$\frac{4326}{H\gamma}$	$\frac{H\gamma}{4352}$	$\frac{H\gamma}{4383}$	$\frac{H\gamma}{4405}$	$\frac{H\beta}{4872}$	$\frac{H\beta}{4957}$	*Bands*
Groom. 3357	0.0	−5.3	+7.0	+4.3	+7.0			
Pi 0^h130		+3.7	+0.7		−1.3	+3.3	+1.0	
Groom. 145		+5.3	−2.0		−4.0	−0.2	−1.8	
Lal. 19022		+6.3	−3.3		−5.0	−1.3	−3.3	1

With the aid of tables constructed from the curves we obtain the following determinations of spectral type from the separate pairs of lines:

		Mean	*Probable Error*
Groom. 3357	F7 F7 F4 F6 F5	F6	±1.0
Pi 0^h130	G7 G5 G6 G4 G5	G5	0.8
Groom. 145	K1 K1 K3 K3 K2	K2	0.6
Lal. 19022	K7 K7 Ma K6 K6	K7	1.6

The average probable error of the determination of type for these four stars is ± 1.0, and this is about the value obtained for several hundred stars classified in this way. It is evident that the accuracy will be

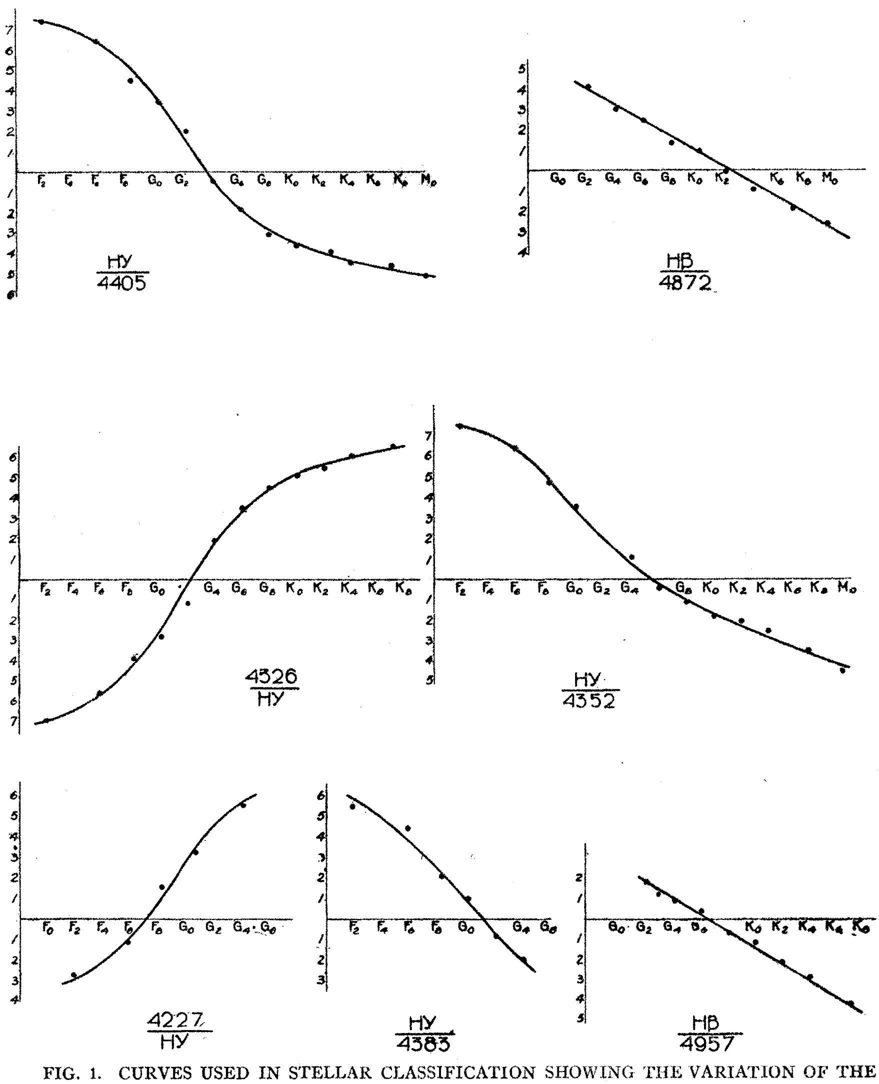

FIG. 1. CURVES USED IN STELLAR CLASSIFICATION SHOWING THE VARIATION OF THE RELATIVE INTENSITIES OF PAIRS OF LINES WITH SPECTRAL TYPE. THE ORDINATES ARE THE DIFFERENCES OF RELATIVE INTENSITY.

least when the lines compared differ greatly in intensity, as in the types F0 – F9 and K5 – Ma, and greatest when the lines are of nearly equal intensity.

This simple method of classification may be recommended as being rapid of operation, and free from the difficulties connected with the comparison of separate photographs with one another. It requires the establishment of a scale of relative-intensity-estimates by the observer, but this is a very simple matter when the range employed is small. To some extent the scale will be dependent upon the dispersion of the spectrograph employed since several of the lines used are compound in character. With the single prism spectrograph at Mount Wilson the same reduction curves have been used successfully for photographs on which the linear dispersion varies from 16 to 90 angstrom units to the millimeter at the center of the spectrum.

In connection with the classification of stellar spectra a number of photographs have been made with a Koch microphotometer of the intensity curves of some of the pairs of lines employed in the comparison. There are numerous practical difficulties connected with the use of this instrument for lines as narrow and as short as those in stellar spectra, and it is doubtful whether the accuracy obtained is of so high an order as to justify the use of so laborious a method for stellar classification. It is probable, however, that it might be used to advantage in the selection of standard stars of reference in which a knowledge of the absolute intensities of certain spectrum lines would be of great value.

INVESTIGATIONS IN STELLAR SPECTROSCOPY. II. A SPECTROSCOPIC METHOD OF DETERMINING STELLAR PARALLAXES

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The question whether the intrinsic brightness of a star may not have an appreciable effect upon its spectrum is one with important applications in astronomy. If two stars which have closely the same type of spectrum differ very greatly in luminosity it is probable that they also differ greatly in size, mass, and in the depth of the atmospheres surrounding them Accordingly we might hope to find in these stars certain variations in the intensity and character of such spectrum lines as are peculiarly sensitive to the physical conditions of the gases in which they find their origin, in spite of the close correspondence of the two spectra in general. If such variations exist and a relationship may be derived between the intensities of these lines and the intrinsic brightness